Design of Airframe-Integrated, Distortion-Tolerant Propulsion Systems

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United Technologies Research Center

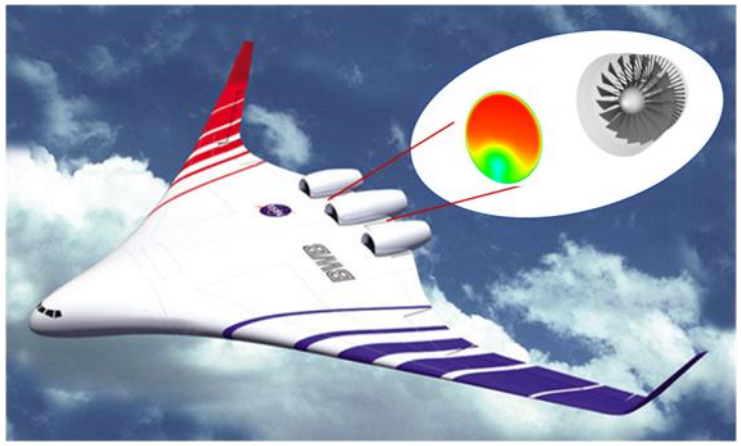
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Acknowledgements

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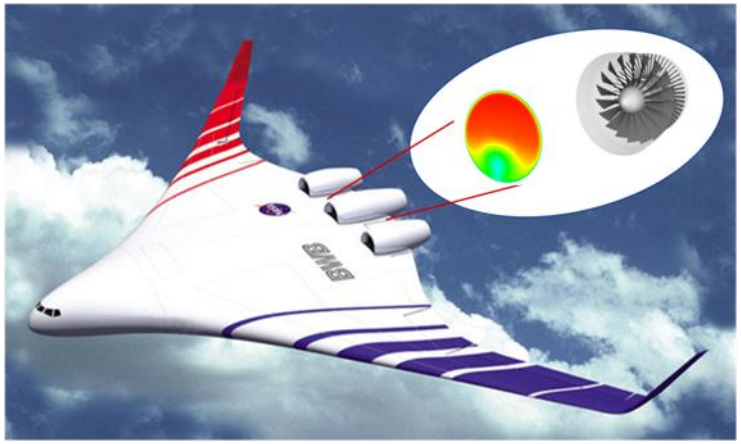
N+2 Program Goals

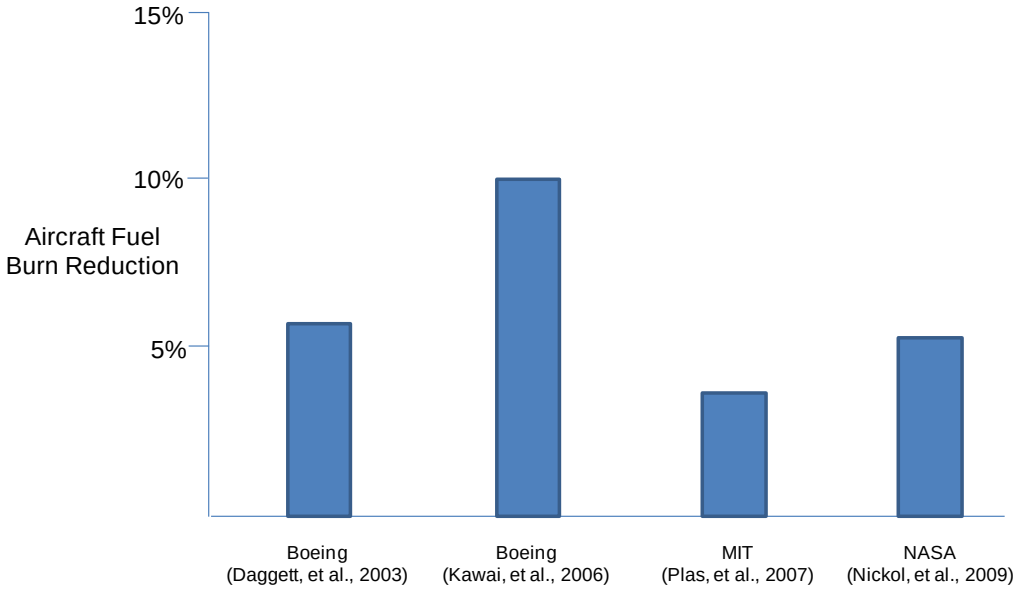


- Update and quantify the expected 5 – 10% achievable BLI vehicle-level performance benefit
 - Leverage previous open-literature BLI system studies
 - Perform high-level, propulsion-system-focused, vehicle-level system study using UTRC's Integrated Total Aircraft Power Systems (ITAPS) experience
- Develop a distortion-tolerant fan stage design that simultaneously targets less than 2% reduced efficiency and less than 2% reduced stall margin relative to a clean-inflow baseline
 - Utilize full-wheel, unsteady 3-D CFD fan design capability
 - Ensure fan design consistent with achieving maximum BLI vehicle-level fuel burn benefits

Previous Studies on BLI Propulsion

Bangert, et al., NASA-CR-3743 (1983)
Daggett, et al., NASA-CR-2003-212670
Berrier, NASA-TP-2005-213766
Campbell, AIAA 2005-0459
Kawai, et al., NASA-CR-2006-214534
Carter, AIAA JOA 2006, Vol 43, No. 5
Plas, MIT PhD Thesis 2006
Plas, et al., AIAA 2007-450
Kawai, NASA-CR-2008-215141
Nikol, NASA-TM-2008-215112
Drela, AIAA 2009-3762
Nikol, McCuller, AIAA 2009-931

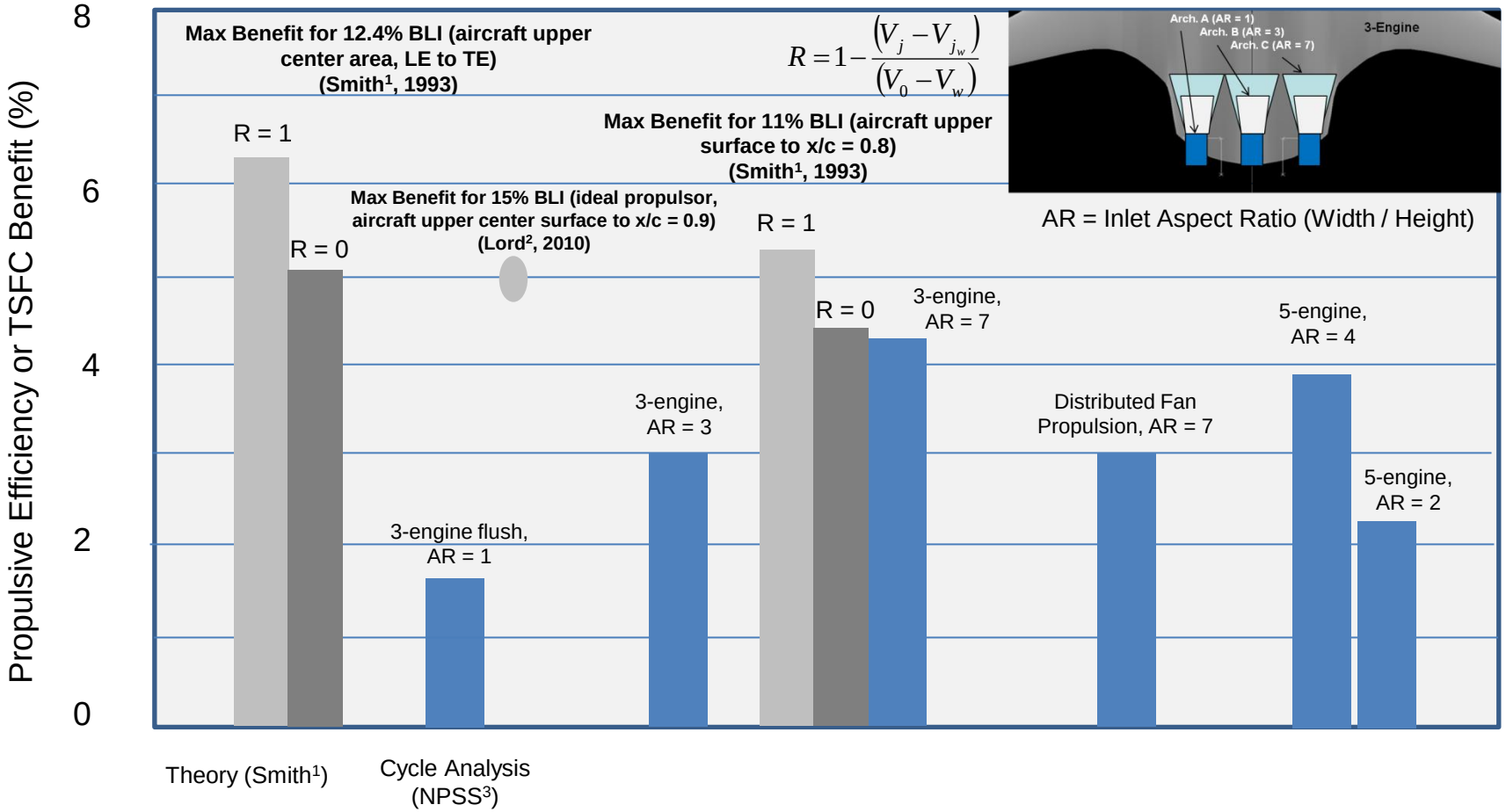




Limiting Theoretical Benefits

Propulsive Efficiency BLI Benefit for Advanced HWB Aircraft (Boeing N2A-EXTE) Relative to Clean-Inflow, Advanced Technology Podded Baseline

[1]Smith, L. H., *Wake Ingestion Propulsion Benefit.* AIAA Journal of Propulsion and Power, Vol. 9, No. 1, Jan. – Feb., 1993
[2]Lord, W. K., *Personal Communication.* Pratt & Whitney, May 2010
[3]Tillman, T. G., Hardin, L. W., Moffitt, B. A., Sharma, O. P., Lord, W. K., Berton, J., and Arend, D., *System-Level Benefits of Boundary Layer Ingesting Propulsion.* Invited presentation, AIAA 49th Aerospace Sciences Meeting, January 2011.



Propulsion / airframe integration configuration can determine ingested boundary layer drag fraction & resulting maximum achievable upper benefit

System Study Approach

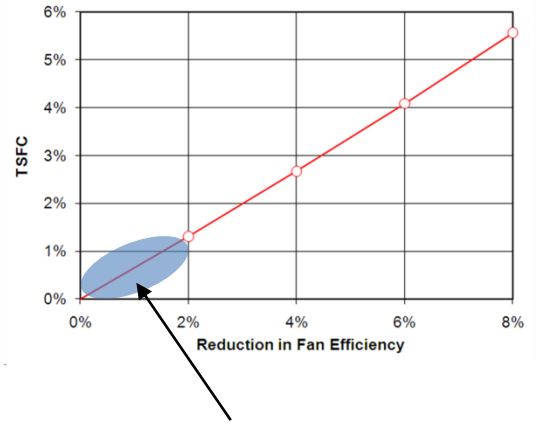
- *High-level system study to define design directions & enabling technology investments*
- *Advanced technology baseline propulsion system (BPR = 16, FPR = 1.35 UHB propulsion system)*
- *Study based on engine sensitivities & aircraft trade factors for a single, advanced UHB engine cycle*
- *Impact of propulsion / airframe integration and engine weight not addressed (i.e., aircraft volume changes, external contour modifications, inlet / airframe design, etc.)*
- *Engine sensitivities obtained using NPSS models; other inputs from simple, low-order models*
- *Aircraft trade factors from ITAPS advanced commercial transport aircraft (similar to Boeing BWB reference aircraft)*

Parameter	Units
Engine BLI benefit	% TSFC
Nacelle drag reduction	% Aircraft Drag
Nacelle weight reduction	% TSFC
Inlet weight increase	% TSFC
Inlet excess pressure loss	% TSFC
Flow control bleed / hp extractions	% TSFC
Fan efficiency reduction	% TSFC

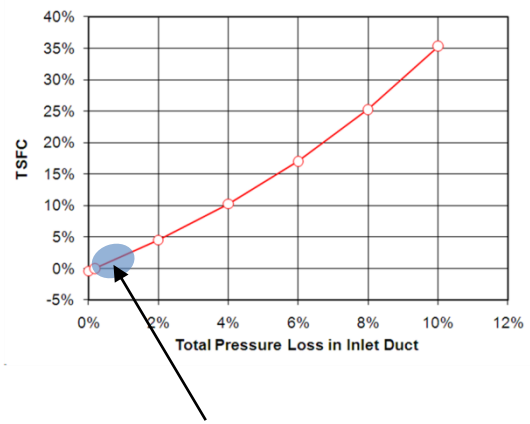
BLI Benefits

BLI Penalties

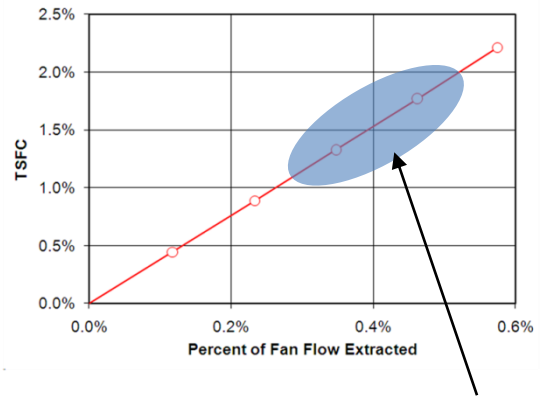
Engine Sensitivities Help Identify Technology Challenges:



High-performance, distortion-tolerant fan



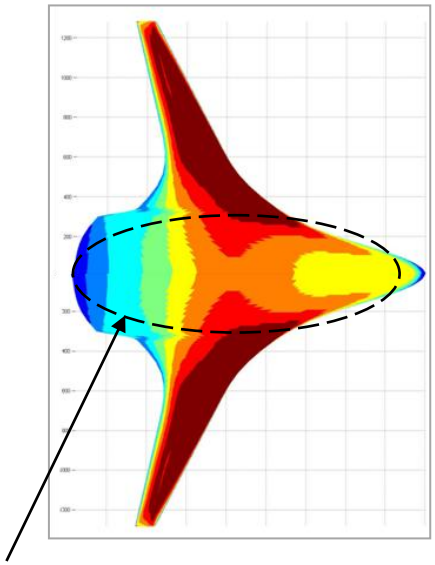
Low-loss, distortion-optimized inlet



Flow control extraction penalties challenging in light of limiting theoretical benefits

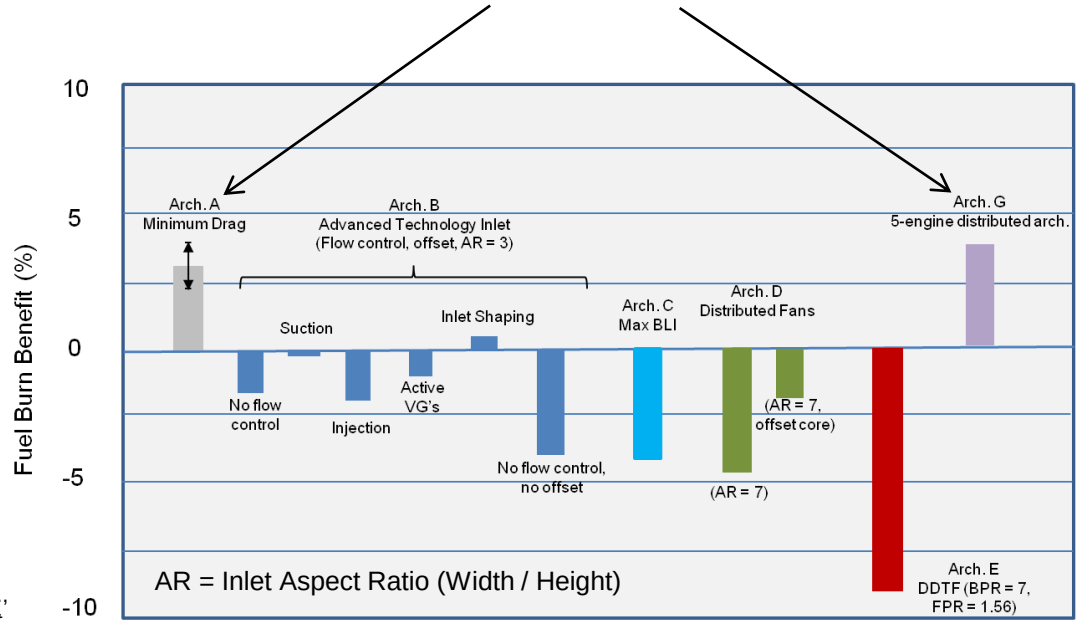
System Study Results

- Boeing N2A-exte reference vehicle (using UTRC ITAPS large commercial transport blended vehicle trade factors)
- Podded, aft, advanced technology UHB baseline propulsion system (BPR = 16, FPR = 1.35)
- 5-engine architecture relative to 5-engine podded baseline to highlight BLI benefit
- Study was carried out for a fixed engine cycle and did not incorporate engine weight or propulsion / airframe integration effects on the aircraft
- Comparatively small ingested drag fraction for the study aircraft limits the maximum achievable benefit (upper, center fuselage boundary layer yields D / T ~12-15%)



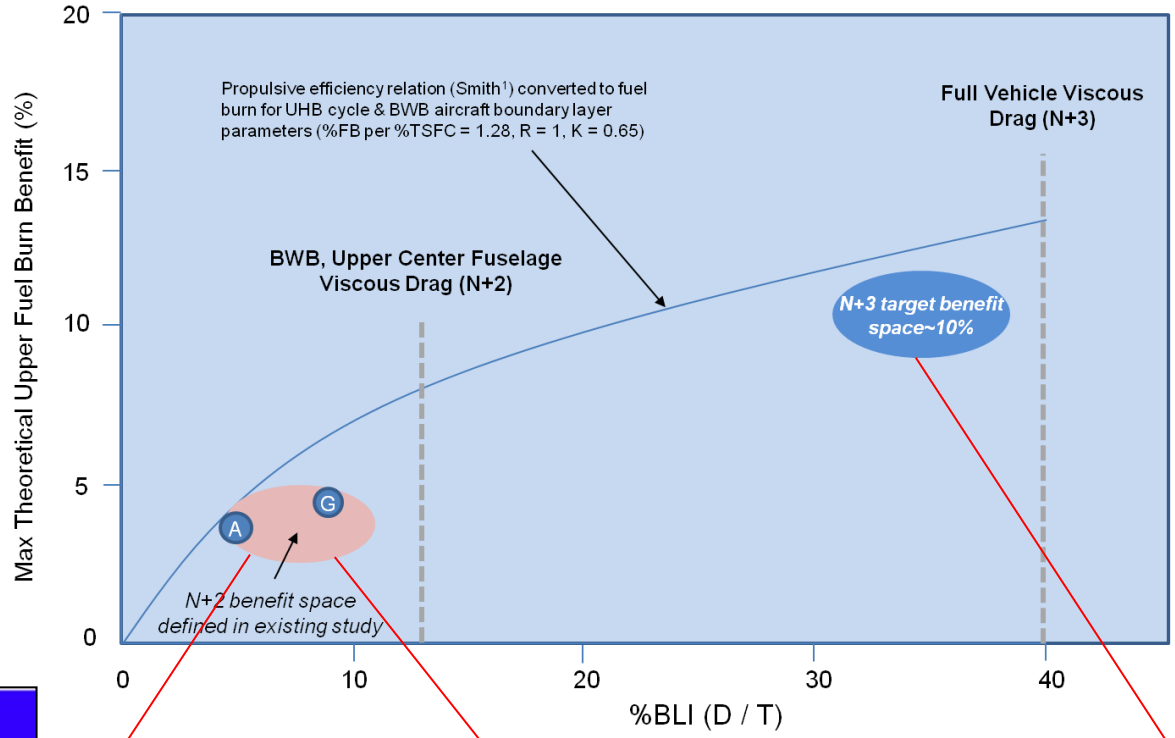
BLI benefit limited by viscous drag accessible on N+2 vehicle upper surface (D / T = 12-15%)[1]

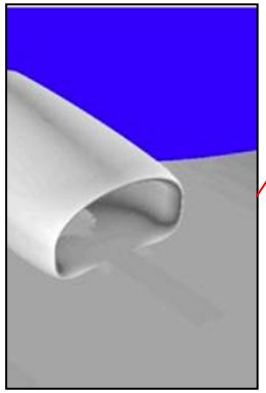
Propulsion system architectures that provide system-level benefits require low-loss, low-drag inlets



[1]Figure & CFD solution from the Boeing Company, Kawai, R. T., Friedman, D. L., and Serrano, L., *Blended Wing Body (BWB) Boundary Layer Ingestion (BLI) Inlet Configuration and System Studies,* NASA CR-2006-213534, December 2006.

System Study Identifies Key BLI-Enabling Technologies





Compact, low-loss, low-drag inlet

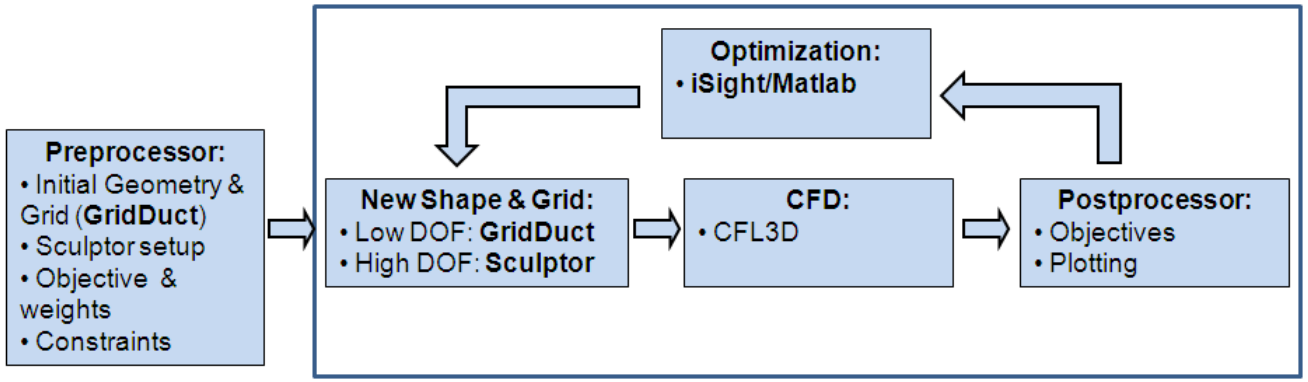


High-performance, distortion-tolerant turbomachinery

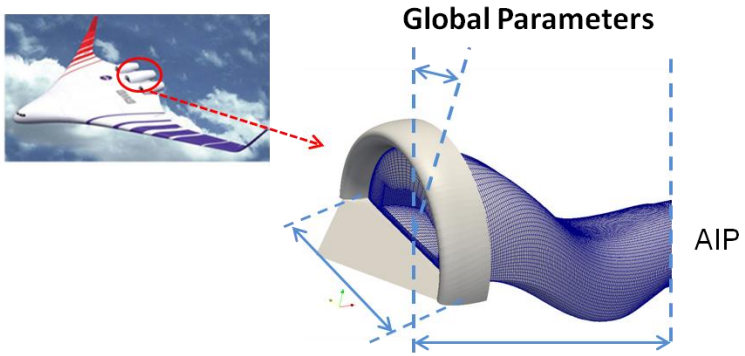


- *Inlet flow control*
- *Laminar flow wings*

Optimization-based Parametric Inlet Design for Embedded Propulsion

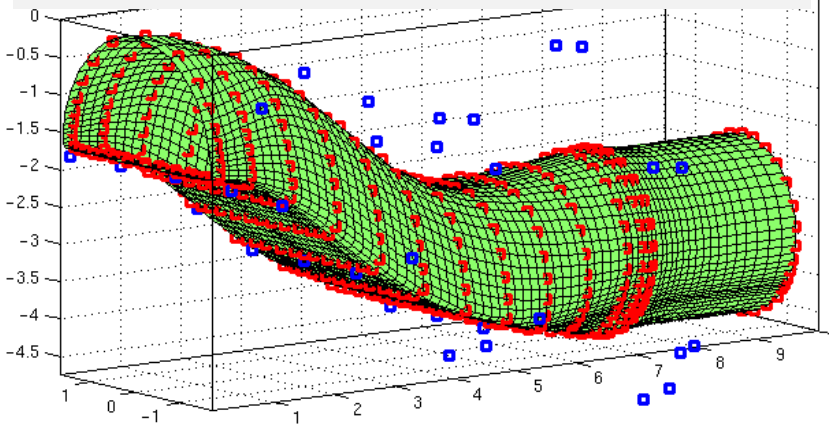


- *Automated optimization enables exploration of wide regions of multi-parameter design space*
- *Toolset can analyze over 1000 cases in a week*
- *New grid morphing capability (SCULPTOR) key enabler*



- Inlet aspect ratio
- Lip contour & thickness
- Duct offset & length
- Wall curvature & shape
- Upstream airframe contour

25 global control points (blue) manipulate ~3000 detailed mesh control points (red)



Distortion-Optimized Inlet Design Progression

NASA Inlet A: Baseline (AR = 1.9, L / D = 3, highly offset)

UTRC A: Shape-optimized Inlet A with flow control

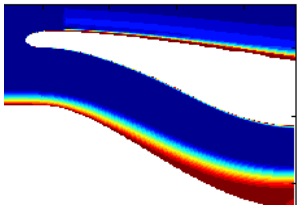
UTRC PA: Improved UTRC A with use of high-fidelity, viscous CFD and automated optimization

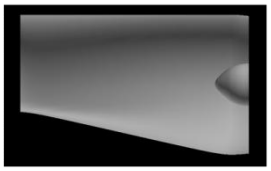
UTRC P1: Point of departure for global optimization; reduced L / D from 1.5 to 0.8; implemented reduced offset

UTRC P2: Local inlet wall shape optimization of P1

UTRC P3: Combined global / local shape optimization including inlet lip & U. S. airframe contour

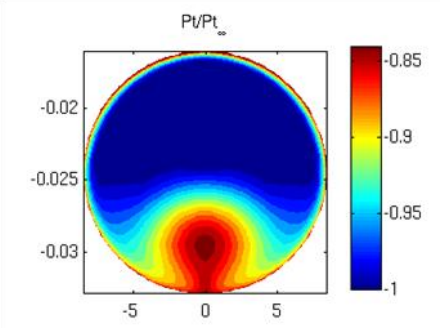
UTRC P4: Final inlet design including optimization of inlet lip & U. S. airframe contour; L / D reduced from 0.8 to 0.6



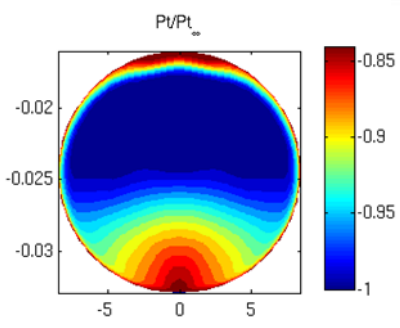


Point of departure for UTRC P-series inlets

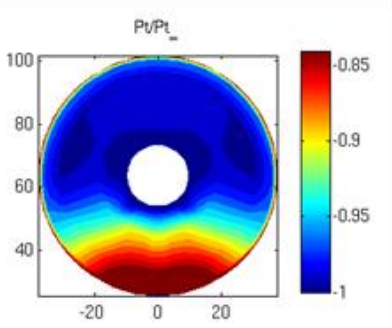
Inlet A



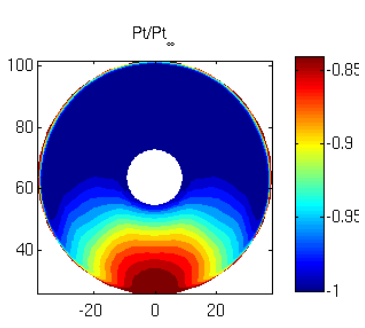
UTRC A



UTRC P1



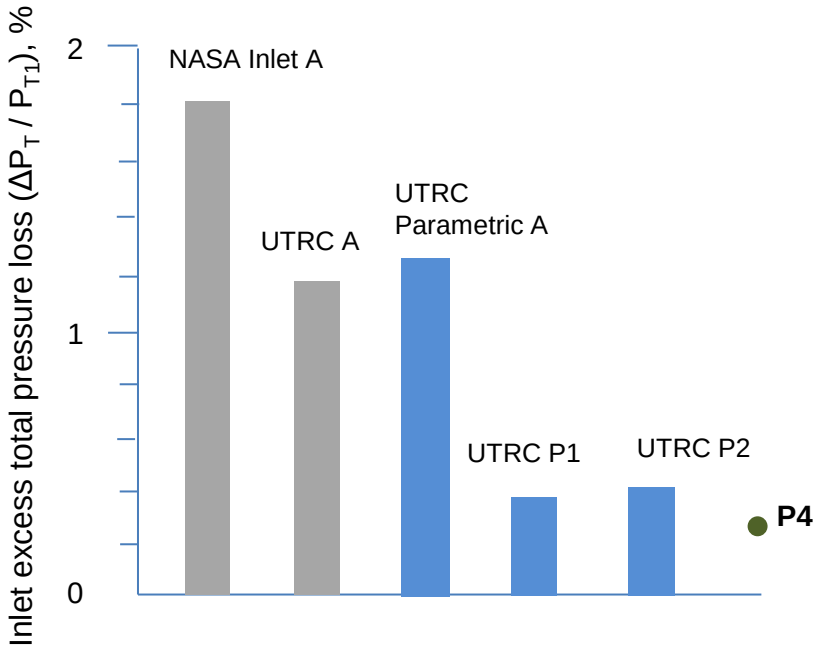
UTRC P4

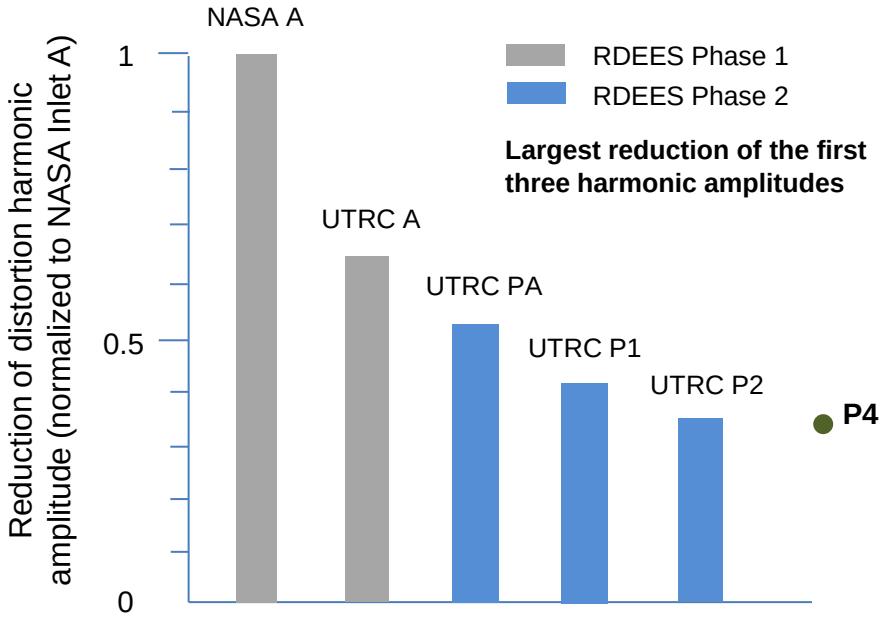


Aerodynamic Interface Plane (AIP) total pressure contours

Optimization-based Parametric Inlet Design
Design progression summary

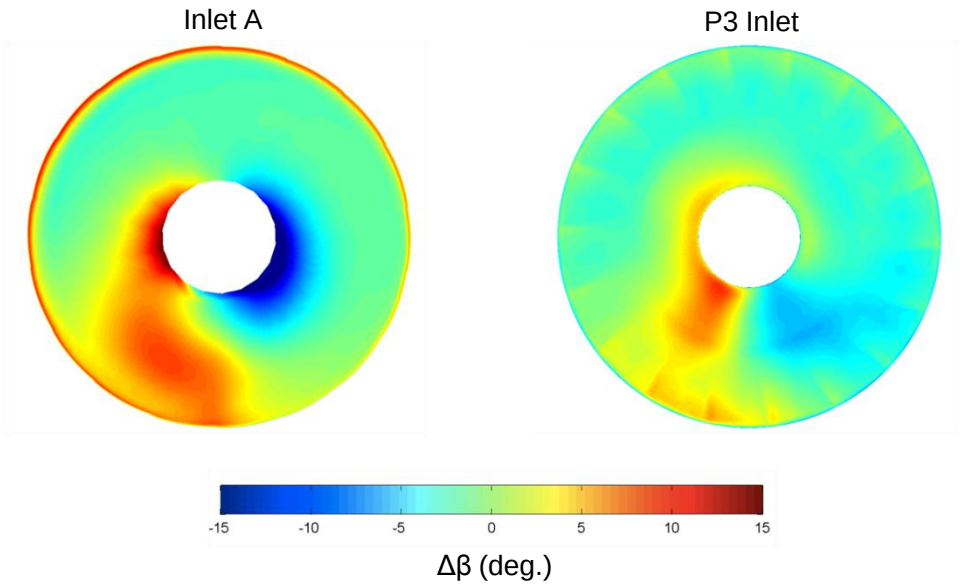
- *Inlet excess pressure loss reduced ~3x relative to Phase 1 optimized inlet & ~4 – 5x relative to original Inlet A starting point*
- *Dominant distortion harmonic amplitudes reduced ~30 – 50% relative to original Inlet A starting point*





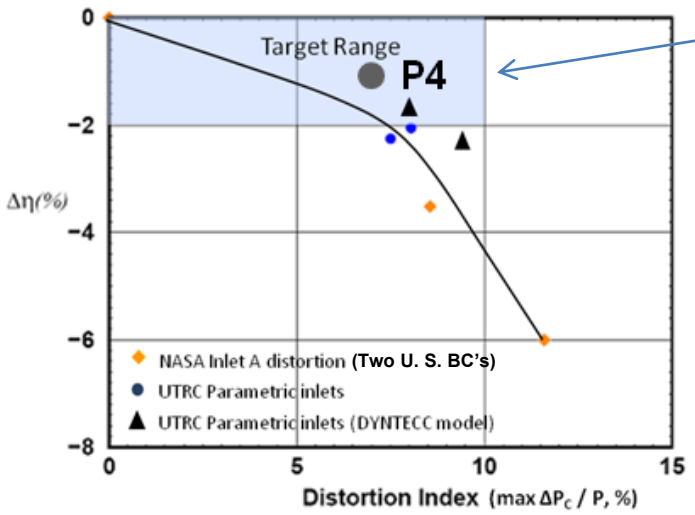
Fan Response to Distortion-Optimized Inlet

Excursions in Fan Blade L. E. Relative Incidence from Clean Inflow



Inlet significantly improves fan interaction with incoming distortion

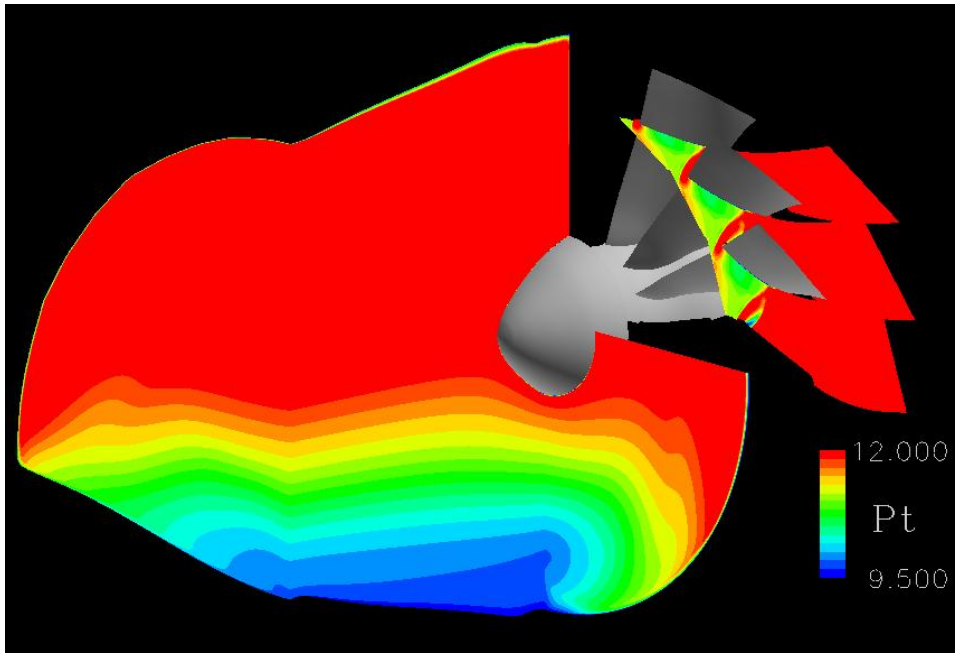
Fan Efficiency Reduction (%)



Inlet enables fan to meet performance target

Fully-Coupled Inlet / Fan CFD Analysis

- *Initial coupling with inlet / fan; steady CFD analysis completed*
- *Converged solution used to initialize fully-coupled inlet / fan / FEGV unsteady CFD case (~80M grid points, ~100+ processors)*
- *Fully-coupled unsteady analysis currently in progress to validate inlet & fan designs*
- *Future work can extend coupling to include entire propulsion system and airframe domain*



Conclusions

- **A high-level, trade-factor-based system study has demonstrated that significant system-level benefits can be achieved with BLI propulsion**
 - Study used a fixed, ultra high bypass ratio advanced engine cycle and Boeing N+2 BWB aircraft; engine weight & propulsion / airframe integration effects were not considered
 - ~3 – 5% fuel burn benefit identified for current N+2 study
 - Significantly larger benefits (order ~10%) are possible for N+3 configurations where more airframe boundary layer may be ingested into the engines
 - The benefits of flow control were found to be largely offset by engine extraction penalties for N+2 airframe & limited BLI available to the engines (flow control likely to trade better for N+3 configurations with higher BLI fractions)
 - Benefits are relative to an aggressive baseline (pylon-mounted advanced UHB propulsion system)
- **The system study has identified a low-loss inlet and high-performance, distortion-tolerant turbomachinery as key technologies consistent with achieving net system level benefits**
- **Optimization-based parametric design has yielded a significantly improved inlet that meets the requirements identified in the system study**
 - Inlet excess pressure losses reduced by ~3-5X
 - Dominant distortion harmonic amplitudes reduced ~30-50%
 - Inlet length reduced by over 50% relative to P-series inlet initial geometry
 - Fan efficiency loss reduced from 6% to 1-2%
- **Preliminary design results show that coupling effects (airframe / inlet / fan / FEGV) will likely play a key role in BLI propulsion design**